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Recent Highlights from VERITAS

R. Mukherjee for the VERITAS Collaboration

Department of Physics and Astronomy, Barnard College, Columbia University, New York, NY 10027

Abstract

VERITAS is a ground-based gamma-ray observatory consisting of an array of four atmospheric Cherenkov telescopes located in southern Arizona, USA. VERITAS carries out an extensive observation program of the gamma-ray sky at energies above 0.1 TeV. Observations of Galactic and extragalactic sources in the TeV band are sensitive probes of the highly energetic processes occurring in these objects. Observations by VERITAS of the Galactic center and nearby dwarf spheroidal galaxies provide constraints on particle dark matter with masses above a few hundred GeV. VERITAS observations also provide constraints on fundamental physics and cosmology, such as probing the history of galaxy formation and studying Lorentz invariance violation (LIV). The majority of the sources detected by VERITAS are active galactic nuclei (AGN), with gamma-ray emission originating in their relativistic jets. TeV observations of AGN help us constrain models of particle acceleration and energy dissipation in relativistic jets, and the size and location of the gamma-ray emission region. Galactic sources at TeV energies include supernova remnants, pulsar wind nebulae, and binary systems, and TeV emission is a key diagnostic of the highly energetic particles in these objects. VERITAS observations provide important clues on the origin of cosmic rays and on particle acceleration in supernova blast shocks and relativistic pulsar wind-termination shocks. In this article I will present some highlights of particle-astrophysics measurements made with VERITAS.

1. Introduction: VERITAS

VERITAS (Very Energetic Radiation Imaging Telescope Array System) is an imaging atmospheric Cherenkov telescope array consisting of four 12m-diameter telescopes of Davies-Cotton design, located at the base camp of the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona. VERITAS uses ground-based detection techniques to explore the Universe in very-high-energy (VHE) gamma rays from 85 GeV to 30 TeV. Each VERITAS telescope has a camera at its focal plane comprising 499 photomultiplier tubes (PMTs) arranged in a hexagonal pattern and has a field of view of diameter 3.5°. Cherenkov light generated in gamma-ray or cosmic-ray showers in the atmosphere is focused on the camera to form an image of the shower. Imaging atmospheric Cherenkov telescopes (IACTs) such as VERITAS utilize the Cherenkov light emitted from air showers to form an image on the camera plane that has information on the longitudinal and lateral development of the air shower. Cosmic rays also produce showers of charged particles and Cherenkov radiation but at a rate much higher than that of gamma-ray showers, and constitute the principal source of background. Using the four VERITAS telescopes in combination helps in obtaining a stereoscopic image of the particle showers to reduce cosmic ray background. VERITAS has an angular resolution of $< 0.1°$ (68% containment) at 1 TeV and an energy resolution of 15% - 20%. Figure 1 is a photograph of the VERITAS observatory, showing the array of four telescopes. Further details of the VERITAS telescopes are provided elsewhere [1].

VERITAS started four-telescope operations in 2007 and has since then undergone a series of upgrades and

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Figure 1: The four VERITAS telescopes located at the base camp of the Whipple Observatory in southern Arizona. This configuration of the array has been in use since 2009.

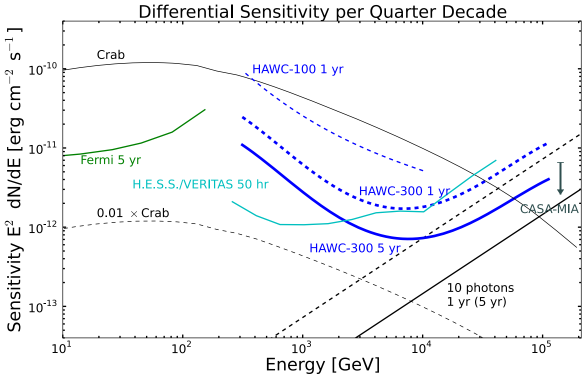

Figure 2: The differential sensitivity of Fermi (green), VERITAS/HESS (cyan), and HAWC (solid blue) over four decades of energy from 1 GeV to 100 TeV. Figure from Abeysekara (2013) [5].

improvements (see [2]). In 2009 one of the telescopes was relocated to provide a more symmetric array layout. This rearrangement together with a new alignment system which improved the instrument point spread function [3] allowed for a 30% improvement in sensitivity. In the summer of 2012 the VERITAS cameras were replaced with new photomultiplier tubes with peak quantum efficiency of greater than 32% [4] that increased the photon detection efficiency of each camera by approximately 50%. VERITAS is able to detect a source with a Crab Nebula-like spectrum and a flux of 1% Crab Nebula strength in about 25 hours. VERITAS now typically collects more than 1100 hours of data per year (including 200 hours data taken in moderate moonlight). VERITAS is normally operated using the full four-telescope array. A multi-level trigger system is employed to eliminate background noise at the array-level. A trigger requires simultaneous Cherenkov images in at least two telescopes, within a 50 ns time window, which then causes a readout of the 500 MSample/s Flash-ADC data acquisition system for each pixel.

VERITAS observations target a rich variety of science at energies greater than 85 GeV, including fundamental physics and cosmology, as well as Galactic and extragalactic astrophysics. The origin of the highest energy cosmic rays remains a mystery and neutral messengers such as gamma rays and neutrinos are perhaps the best probes for directly observing cosmic accelerators. Observations performed with VERITAS have led and will continue to lead to significant progress in our understanding of the accelerators of very high energy particles in the Universe. VERITAS observations are complementary to observations with the Fermi Large Area Telescope (Fermi-LAT) and the Gamma-Ray Burst Monitor (GBM) at lower energies, and to the High Altitude Water Cherenkov (HAWC) Experiment at higher energies. While IACTs have small fields-of-view (FOVs), they have the advantage of large effective areas and the ability to achieve better source localization compared to satellite experiments such as Fermi. Figure 2 shows the differential sensitivities of the different gamma-ray experiments currently in use and planned for the future [5]. The combined sensitivities from ~ 300 MeV to 100 TeV allows complementary studies to probe some particle physics processes in the Universe. In this article, we review some of the recent results from VERITAS.

2. Science with VERITAS

The VERITAS science program is based on four themes of scientific exploration: (a) particle physics and fundamental laws, (b) cosmology, (c) black holes and (d) galactic tevatrons and pevatrons. Summaries of the VERITAS science goals addressing fundamental physics topics and details of the long-term program related to the indirect detection of dark matter were recently presented in two white papers [6, 8] that describe the critical role that the VERITAS Observatory will play in the future of the U.S Cosmic Frontier program. Fundamental physics topics of interest include studies of antimatter, the search for primordial black holes, study of cosmology utilizing unique probes of the extragalactic background light (EBL) & and the intergalactic magnetic field (IGMF), & Lorentz invariance violation (LIV). VERITAS also plays an important role in multi-messenger astrophysics and has the capability to complement the results being produced by ultra high energy cosmic ray (UHECR) instruments such as Auger and neutrino observatories such as IceCube. In the following we present a brief (and incomplete) summary of a few selected results; we refer the reader to the compilations of articles presented at the recent ICRC [9] for a more compete description of VERITAS results.

2.1. Dark Matter Studies

Indirect dark matter searches constitutes a substantial fraction of the VERITAS observations. VERITAS dark matter searches are motivated by the compelling evidence for the presence of non-baryonic dark matter in various structures of the Universe. Weakly interacting massive particles (WIMPs) in the mass range of 50 GeV - 10 TeV are well motivated dark matter candidates in extensions of the Standard Model of particle physics (supersymmetry, Kaluza-Klein). The neutralino, the lightest SUSY particle, is the most commonly used candidate and self-annihilates to produce gamma rays.

VERITAS observes a variety of dark matter targets with the goal of selecting the best candidates depending on the mass to light ratio, distance and astrophysical background levels. VERITAS dark matter targets include (a) the Galactic Center, which although a nearby source and a strong dark matter candidate, has the need to characterize well the large astrophysical gamma-ray background. (b) Dwarf spheroidal galaxies (dSphs): These are gravitationally bound objects with large mass to light ratios, that are believed to contain up to O(1000) times more mass in dark matter than in visible matter, making them widely discussed as potential targets for indirect dark matter detection. Although these are attractive targets with no gamma-ray background, their dark matter distribution can be uncertain, which can pose a challenge. (c) Unidentified Fermi-LAT sources: These are Fermi-detected gamma-ray sources with no known counterparts at other wavelengths. It is likely that the Galactic ones are local and could potentially be candidates for dark matter targets, although their nature and distance are unknown. (d) Galaxy Clusters: These have the largest dark matter concentration in the Universe, but their distance is large, the sources are extended and the gamma-ray signal weak. Here we discuss a few of the results from observations of dSphs; for more detailed reviews on the VERITAS dark matter results, see [6, 11].

Figure 3 shows the VERITAS 95% confidence level limits on the dark matter velocity-weighted annihilation cross-section $<\sigma v>$ for five dSphs observed with VERITAS: Segue 1, Ursa Minor, Draco, Bootes and Willman 1. The figure represents 48 hours of data on Segue I and $\sim 15-20$ hrs on the other targets [6]. Figure 4 shows the 95% confidence level upper limits from the VERITAS observations of Segue 1 on the WIMP $<\sigma v>$ as a function of the WIMP mass, considering different final state particles. The grey band area represents a range of

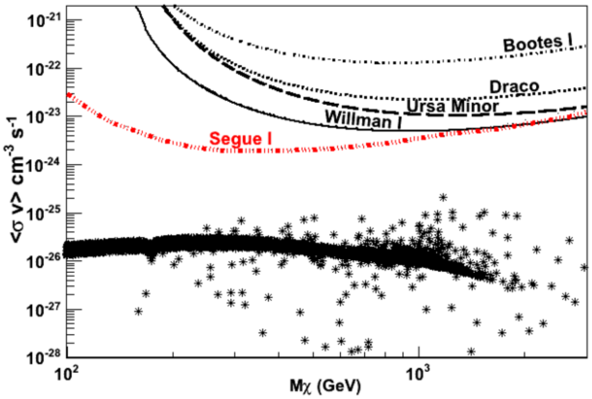

Figure 3: Results from VERITAS observations of dSphs on the velocity-weighted annihilation cross-section $<\sigma v>$ as a function of WIMP mass. The black asterisks represent points from MSSM models that fall within ±3 standard deviations of the relic density measured in the three-year WMAP data set [7]. Figure from Smith et al. (2013) [6].

generic values for the annihilation cross-section in the case of thermally produced dark matter. Although the VERITAS 95% limits are $\sim$ 2 orders of magnitude away from the canonical cross section, VERITAS results do constrain some models which predict large boosts, both astrophysical in nature from clumping of dark matter within the galaxy and from particle physics processes (i.e. Sommerfeld enhancements) [10].

With continued observations in the future, VERITAS will provide increased sensitivity to neutralino dark

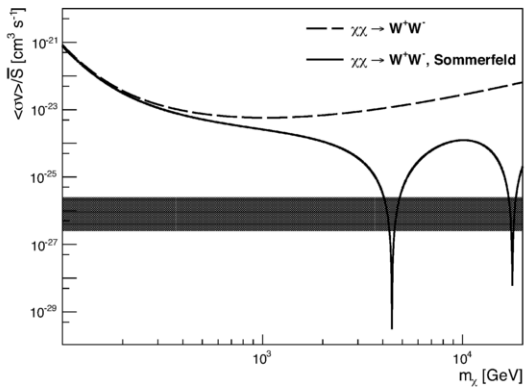

Figure 4: 95% CL exclusion curves from the VERITAS observations of Segue 1 on the velocity-weighted annihilation cross-section $<\sigma v>$ as a function of the dark matter particle mass, in the framework of models with a Sommerfeld enhancement. Figure from Aliu et al. (2012) [10].

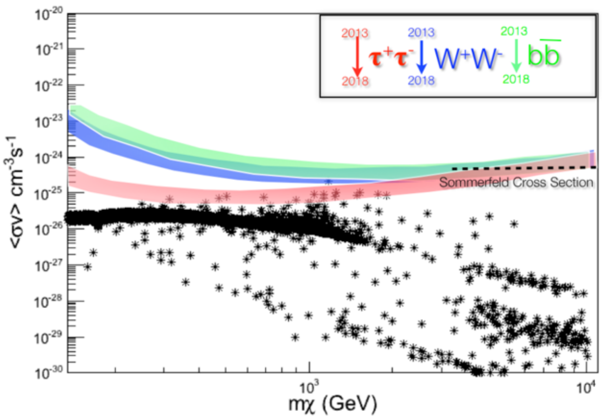

Figure 5: Predicted constraints from VERITAS observations of dSphs on the velocity-weighted annihilation cross-section $<\sigma v>$ as a function of WIMP mass from a stacking analysis for various pure annihilation channels. The black asterisks correspond to points from MSSM models that fall within ±3 standard deviations of the relic density measured in the three-year WMAP data set [7]. Figure from Smith et al. (2013) [6].

matter. Figure 5 shows the projected VERITAS dark matter sensitivity limits from a stacked dSph analysis using data collected through the end of the 2013 observing season and data expected through the 2018 observing season. The power of a stacking analysis is that it allows for a single constraint to be derived from multiple observations. The stacking analysis technique and the predicted constraints from a fully completed VERITAS dark matter program are described elsewhere [6, 12].

2.2. LIV Tests with Pulsars

The detection of pulsed emission from the Crab pulsar above 100 GeV by the VERITAS collaboration [13] provided the opportunity to probe physics at the Planck scale and constrain LIV effects with a sensitivity that is competitive with some of the best available limits. Figure 6 shows the pulse profile of the Crab pulsar above 120 GeV measured with VERITAS, together with the pulse profile measured by Fermi-LAT above 100 MeV. Using this data, Otte [14] derived a one-sided 95% confidence level upper limit on the time difference between the peak positions at 100 MeV and 120 GeV and placed a limit of $E_{LIV} \sim 3 \times 10^{17}$ GeV on the energy scale of LIV.

2.3. Astrophysics Results

VERITAS spends more than 1100 hours per year on source observations. Fig. 7 shows a skymap of

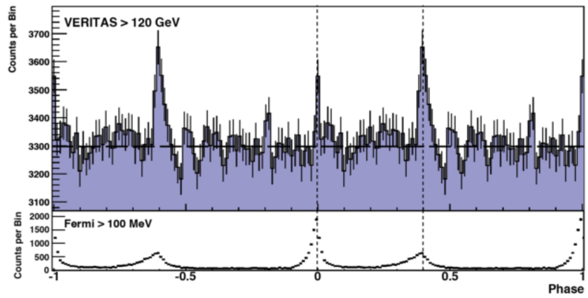

Figure 6: VERITAS (> 120 GeV) and Fermi-LAT (> 100 MeV) pulse profile of the Crab pulsar at gamma-ray energies. VERITAS data taken between 2007 and 2011 was used to make this plot [13, 16].

the VERITAS detections to date. The VERITAS extragalactic source list is dominated by active galactic nuclei (AGN) powered by supermassive black holes (SMBHs), with ultra-relativistic jets (outflows of particles) pointed close to our line of sight. Observations of blazars at TeV energies probe the innermost regions of these powerful particle accelerators, where the bulk of their luminosity is emitted. In addition to understanding the astrophysics of relativistic jets in AGN, TeV observations of blazars will be key to understanding the origin of the highest energy cosmic rays [17]. TeV observations of blazars also provide constraints on fundamental physics and cosmology, such as probing the history of galaxy formation, studying the density and spectrum of the EBL [18], and the strength of the IGMFs [19]. A few recent highlights from the VERITAS observations of blazars are as follows: (a) Detection of rapid variability in BL Lacertae, when the source was detected at a flux of 125% that of the Crab Nebula flux and exhibited rapid variability that placed constraints on the size of the emission region [20]; (b) measuring $E > 0.1$ TeV gamma rays from the blazar PKS 1424+240 out to a distance of at least 7.4 billion light-years (red shift > 0.6035) and carrying out deep, broadband observations of the source [21]; (c) discovery of the new TeV source VER J0521+211, triggered by the detection of a cluster of high-energy photons in the data from the Fermi gamma-ray satellite [22]; (d) deepest ever observation of the relatively distant (z=0.14) VHE blazar 1ES 0229+200 and a three year multi-wavelength study of the source [23]; and (e) long term observations of the blazar B2 1215+30 [24].

Figure 8 shows the broadband spectrum of VER J0521+211 during the VERITAS detection in 2009 [22]. The spectral energy distribution is typical of that for gamma-ray blazars, exhibiting a low energy bump due

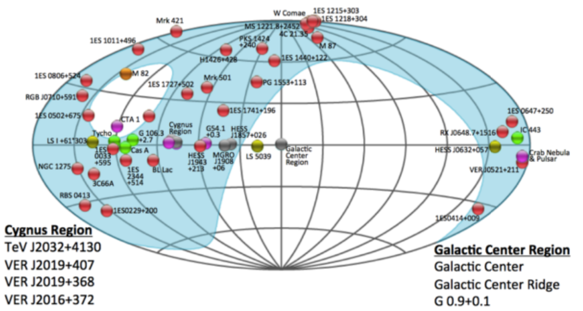

Figure 7: The VERITAS sky map of detected sources as of July 2014, in Galactic coordinates. The shaded area shows the region of visibility for VERITAS.

to synchrtron emission from relativistic electrons in magnetic fields, and a high energy bump which could arise due to leptonic (inverse Compton) or hadronic (pion decay or proton synchrotron) processes. The peak of the high-energy gamma-ray emission from VER J0521+211 is between 10 and 200 GeV. A simple one-zone leptonic relativistic jet model explains the gamma-ray emission as due to synchrotron self-Compton radiation, assuming a particle dominated jet with a bulk Lorentz factor of 30, and requiring a relatively weak magnetic field of 0.01 G [22].

In Galactic physics, VERITAS observations covered the rich Cygnus region. Some recent highlights include: (a) detection of strong TeV emission by VER-

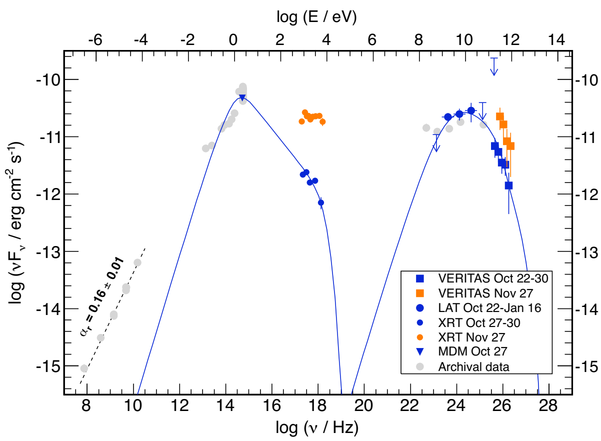

Figure 8: Broadband spectral energy distribution of VER J0521+211 during the VERITAS detection in 2009. The orange markers correspond to the flare data. The solid blue curve represents a one-zone synchrotron self-Compton emission model with parameters adjusted to describe the low-state data. For details on the broadband data and modeling results, see Archambault et al. (2013) [22].

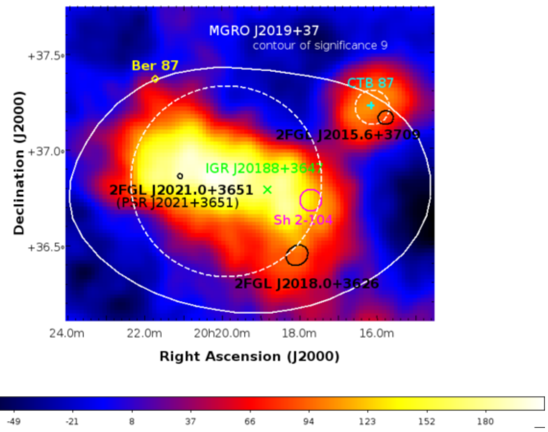

Figure 9: VHE gamma-ray excess map of the MGRO J2019+37 region as observed by VERITAS above 600 GeV. The color bar indicates the number of excess events within a search radius of 0°.23. Figure from Aliu et al. (2014) [25].

ITAS from the MGRO J2019+37 region which helped to resolve the mysterious Milagro sources in Cygnus-X [25]. Figure 9 shows the VERITAS VHE excess map of the MGRO J2019+37 region as observed above 600 GeV. (b) Investigation of the TeV Morphology of MGRO J1908+06 with VERITAS [26]. The VERITAS results suggest a complex region with the TeV emission possibly arising due to interaction between the energetic particles emitted by a pulsar and either the SNR or molecular clouds. (c) VERITAS reported observations of the unidentified gamma-ray source TeV J2032+4130 and suggested that the TeV emission could be the result of a pulsar wind associated with the recently discovered Fermi-LAT pulsar PSR J2032+4127 [27]. And, (d) VERITAS published results on the long-term observations of the gamma-ray binary HESS J0632+057 [28].

3. Summary

The scientific reach of VERITAS covers the study of both extragalactic and Galactic objects as well as the search for astrophysical dark matter. Some highlights from VERITAS were presented at this meeting. Dark matter studies continue to be a high priority for VERITAS. Ongoing observations of dark matter targets account for a significant portion of the VERITAS observing time. VERITAS is expected to continue to have a strong observing program.

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